

Northern Illinois University

Measurements with the Danilov-Nagaitsev Magnet (NIO)

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Outline



- Quick run down of Danilov-Nagaitsev Nonlinear Magnet
- Tune Measurements
 - Amplitude Dependent Tune Maps
 - Vertical Amplitude Dependent Tune Shifts
- M2L Sync-Light Measurements
- Outlook and Conclusion

Nonlinear Magnet

Start with a linear focusing accelerator with equal horizontal and vertical optics.

- The linear optics can be built with standard optics, but must have a n- π phase advance, "T-insert"
- Drift region L, matched beta function (L=1.8m in IOTA)

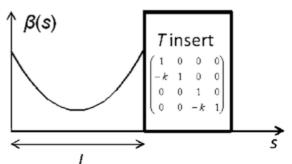
$$H_N = \frac{(p_{xN}^2 + p_{yN}^2)}{2} + \frac{x_N^2 + y_N^2}{2} + U(x_N, y_N, \psi)$$

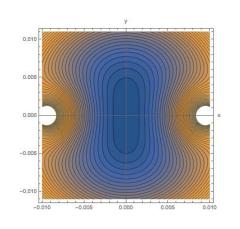
$$U(x,y) = \frac{f(\xi) + g(\eta)}{\xi^2 + \eta^2}$$

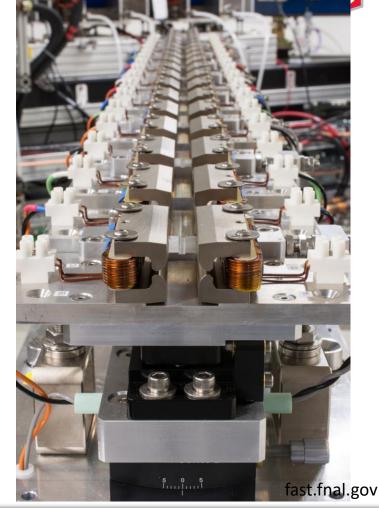
$$f_2(\xi) = \xi \sqrt{\xi^2 - 1} [d + t \operatorname{acosh}(\xi)]$$

$$g_2(\eta) = \eta \sqrt{1 - \eta^2} [b + t \operatorname{acos}(\eta)]$$

$$\xi = \frac{\sqrt{(x+c)^2 + y^2} + \sqrt{(x-c)^2 + y^2}}{2c} \quad \eta = \frac{\sqrt{(x+c)^2 + y^2} - \sqrt{(x-c)^2 + y^2}}{2c}$$







To have lowest multipole expansion term to be a quadrapole: d=0, b = $-\frac{\pi}{2}$ t, t is then the nonlinear potential strength V. Danilov and S. Nagaitsev, Phys. Rev. ST-AB **13**, 084002 (2010)

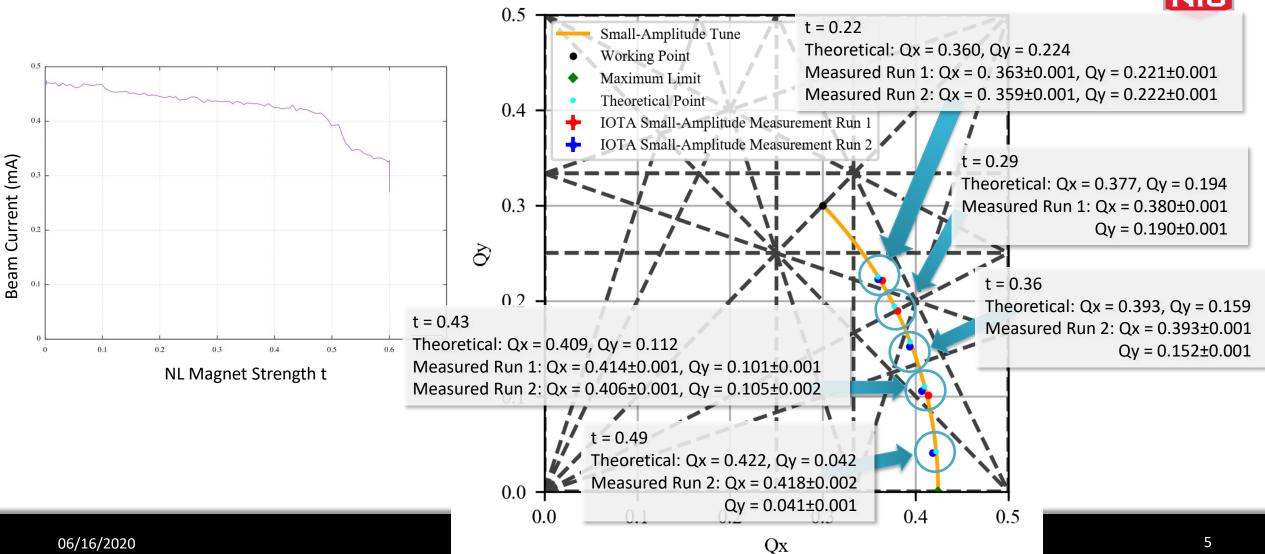
Tune Measurements



- Nonlinear Magnet t-strengths of t = 0.218, 0.42, 0.48
- Calculated tunes via FFT (N=512 turns)
 - Summed FFT Amplitudes from 20 BPM's
- Vertical Amplitude Dependent Tune Shift
- Percentage Beam Loss from BPM Intensity Signal
 - Moving Average of 10 turns from 20 BPM's

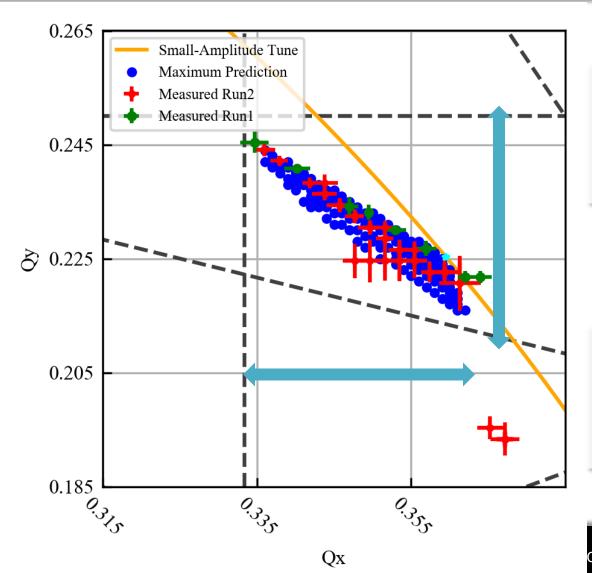
Small-Amplitude Map





Amplitude Dependent Tune Map, t=0.22





Vertical:

Small Amplitude: Qy=0.225

Theoretical Maximum: $\Delta Qy = 0.028$

Measured Run 1: $\Delta Qy = 0.0245 \pm 0.0018$

Measured Run 2: $\Delta Qy = 0.0312 \pm 0.0067$

Horizontal:

Small Amplitude: Qx =0.359

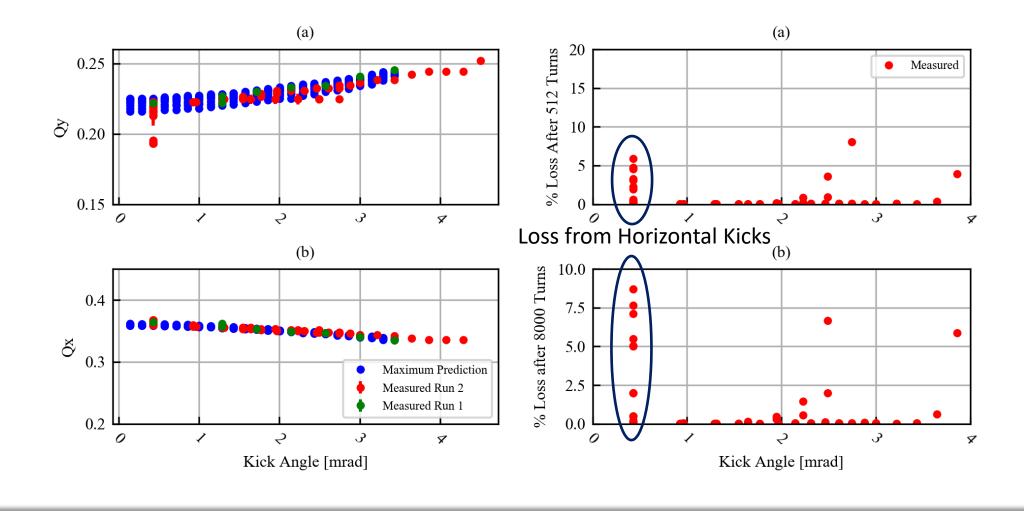
Theoretical Maximum: $\Delta Qx = 0.026$

Measured Run 1: $\Delta Qx = 0.0334 \pm 0.0018$

Measured Run 2: $\Delta Qx = 0.0234 \pm 0.0020$

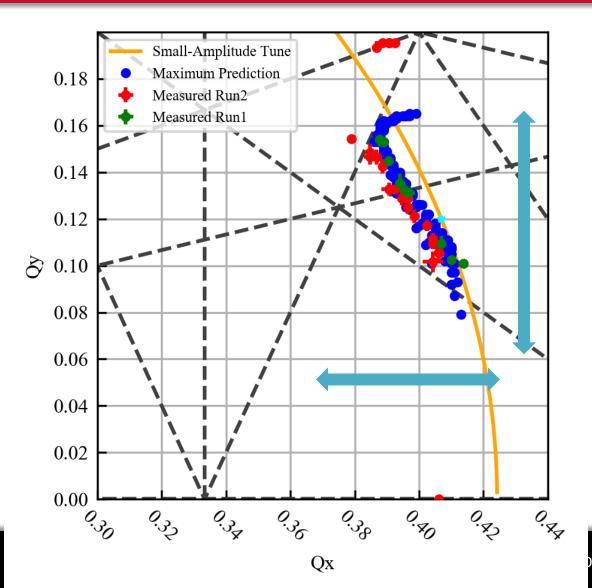
Vertical Amplitude Dependent Tune Shift, t = 0.22





Amplitude Dependent Tune Map, t=0.43





Vertical:

Small Amplitude: Qy=0.12

Theoretical Maximum: $\Delta Qy = 0.085$

Measured Run 1: $\Delta Qy = 0.0530 \pm 0.0018$

Measured Run 2: $\Delta Qy = 0.0524 \pm 0.0013$

Horizontal:

Small Amplitude: Qx =0.406

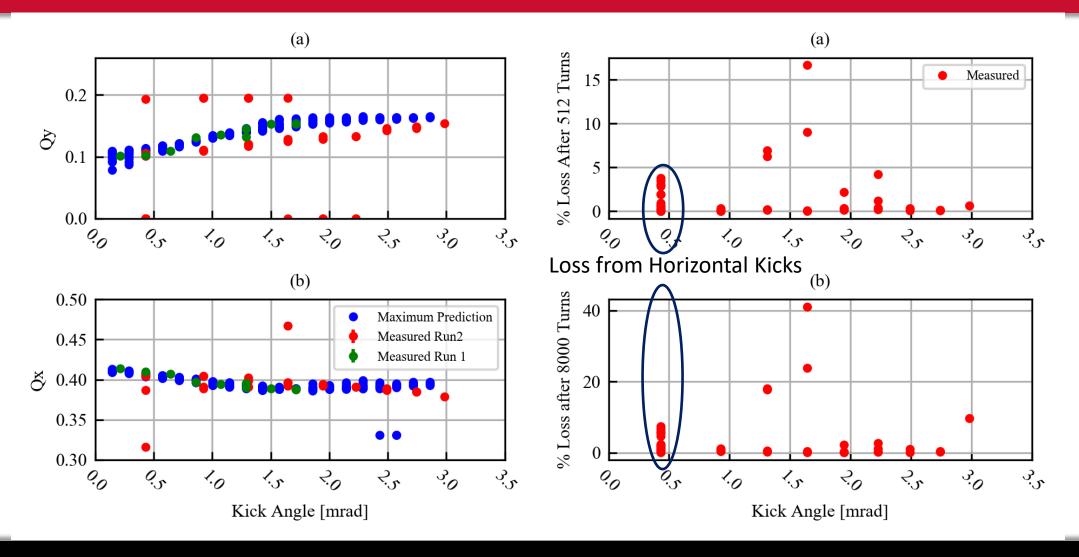
Theoretical Maximum: $\Delta Qx = 0.026$

Measured Run 1: $\Delta Qx = 0.0261 \pm 0.0017$

Measured Run 2: $\Delta Qx = 0.0300 \pm 0.0016$

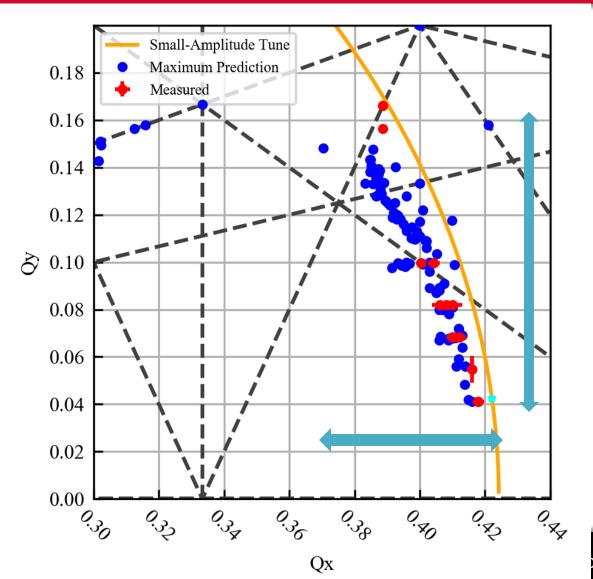
Vertical Amplitude Dependent Tune Shift, t = 0.43





Amplitude Dependent Tune Map, t=0.49





Vertical:

Small Amplitude: Qy= 0.042

Theoretical Maximum: $\Delta Qy = 0.108$

Measured Run 2: $\Delta Qy = 0.125 \pm 0.0016$

Horizontal:

Small Amplitude: Qx = 0.422

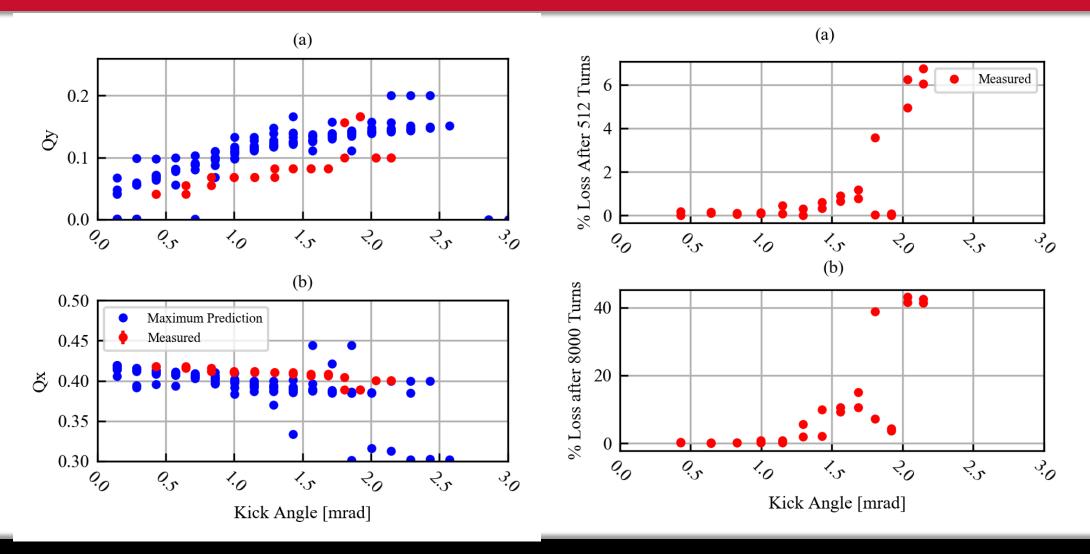
Theoretical Maximum: $\Delta Qx = 0.036$

Measured Run 2: $\Delta Qx = 0.028 \pm 0.0021$

Vertical Kicks only
Significant beam loss after kick.
Chromaticity was not corrected
Had to realign orbit through center of NL

Vertical Amplitude Dependent Tune Shift, t = 0.49





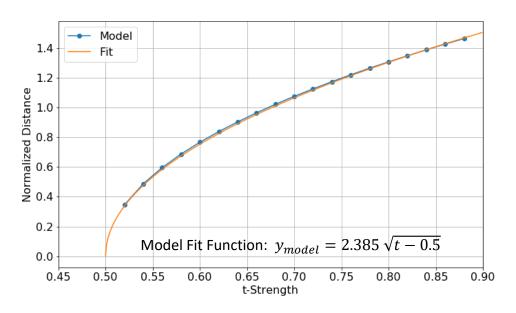
Nonlinear Potential

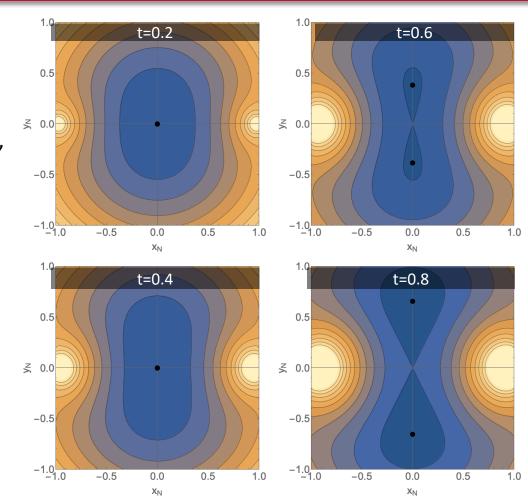


Used Mathematica to find stable fixed points. Potential Expressed as[1]:

$$V(x_N, y_N) = \frac{1}{2}(x^2 + y^2) - t * \Re e(\frac{z}{\sqrt{1 - z^2}} \arcsin(z)),$$

 $z = x_N + iy_N$

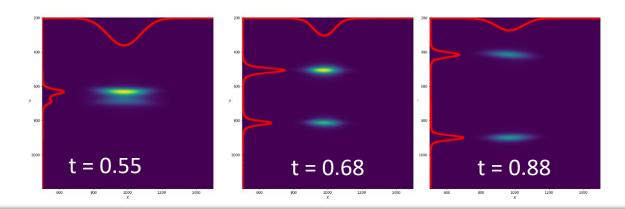


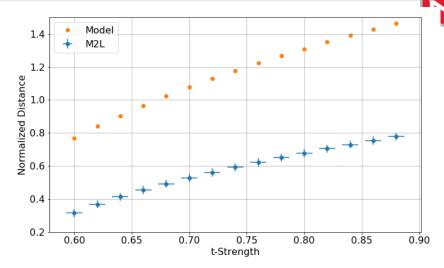


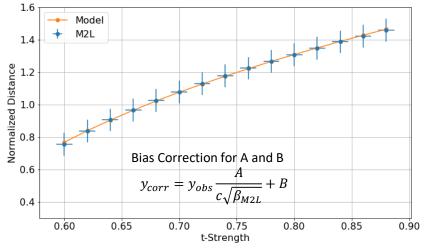
[1] Mitchell, Ryne, and Hwang, Phys. Rev. E 100, 053308 (2019)

Measurements from M2L

- Recorded images with 1 second exposure from synchrotron-light diagnostics
- M2L lattice parameters: $\beta_x \approx$ 3.761 [m], $\beta_y \approx$ 0.199 [m], $D_x \approx$ 0.094472 [m]
- Low Intensity Beam, (survived crossing integer resonance)
 - Stable at fixed points for higher t-strength
- Distance between the two stable fix points increase nonlinear with t-strength.
- Ideal lattice maximum distance = 1.445
 - 10% Error on Beta-function = 1.515
- At t = 0.90, nearing mechanical aperture, one of the beamlets slowly decays
 - Past t = 0.90, limit reached
- Need to further analyze synchrotron light diagnostic systematics.







Summary and Outlook

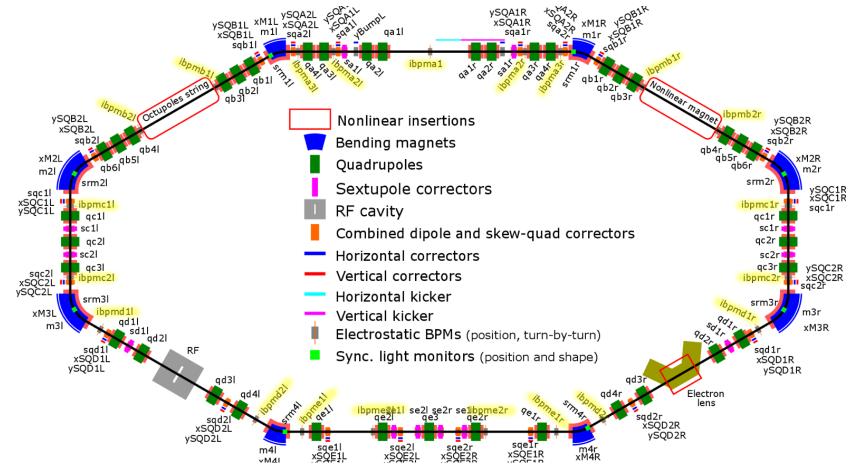


- Run 1 Largest observed tune shift of ΔQx = 0.0261±0.0017 and ΔQy = 0.0530±0.0018 at t = 0.43
- Run 2 Largest observed tune shift of $\Delta Qx = 0.028 \pm 0.0021$ and $\Delta Qy = 0.125 \pm 0.0016$ at t = 0.49
- Successfully split beam into two beamlets
- Future Run improvements,
 - Correct for Resonance Drive Terms
 - Systematically correct chromaticity and orbit alignment for each t-strength step

Integrable Optics Test Accelerator



Parameter	Value
Perimeter	39.97 m
Momenta	50-200 MeV/c
p_{e-beam} , design	150 MeV/c
p_{p-beam} , design	70 MeV/c
Electron current	1.2 mA
Proton current	10 mA
RF frequency	30 MHz
RF voltage	1 kV
ν_x, ν_y, ν_s	$(0.3, 0.3, 5.7 \times 10^{-4})$
$ au_x, au_y, au_s$	(2.0, 0.7, 0.3) s
ϵ_x , $\epsilon_{x,ycoupled}$, RMS	(96.3, 25.3) nm
$\Delta p/p$, RMS	1.26×10^{-4}



Measurements from M2L Images



